ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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REPORT 410

CYCLIC TEMPERATURE EFFECTS ON MATERIALS AND STRUCTURES

by

J. A. DUNSBY

JULY 1962

NORTH ATLANTIC TREATY ORGANIZATION

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This Study was sponsored by the AGARD Structures
and Materials Panel

FOREWORD

The Structures and Materials Panel of AGARD has devoted a considerable proportion of its efforts to the thermal problems of high speed flight. It has long recognised that there are many gaps in existing knowledge of this subject and that one of its prime duties is to stimulate research to fill these gaps. The present report is the result of one such Panel activity.

In mid-1959 the Panel solicited from the author a statement of the current state of knowledge on cyclic temperature effects together with proposals for research as deemed necessary. The first working document resulting from this request was considered by the Panel during its meeting at Aachen in September 1959.

As a result of this meeting the Panel initiated studies of the design and availability of testing machines for testing materials and small components under cyclic temperature conditions. These studies have been completed and an AGARDOGRAPH has been issued. Work was also continued on the review of cyclic temperature effects and a working group was formed to implement the proposal for collaborative research that had been prepared.

Although the working group reported enthusiastically on the research proposals, it found that the commitments of the research laboratories of the NATO nations were such that few were in a position to undertake additional work. It was finally agreed that the review would be brought up to date and that the proposed research programme would be broken down into a number of smaller projects, any of which would be within the capabilities of individual laboratories.

The final version of the report and its list of research projects was approved by the Panel at its meeting in Paris in July, 1962. We hope that publication of this document will stimulate further research in this most important area of material behaviour.

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SUMMARY

A review is made of the present state of knowledge on cyclic temperature effects on materials and structures. Suggestions are made for further research.

SOMMAIRE

L'auteur passe en revue l'état actuel des connaissances sur les effets de température cycliques sur les matériaux et les structures, et suggère des travaux pouvant faire l'objet de recherches ultérieures.

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NOTATION

$\dot{\epsilon}$	creep rate
S	a constant
H	activation energy
R	gas constant
T	temperature
σ	stress
$\phi(\sigma)$	stress function
t	time
t_R	stress-rupture time under isothermal, constant-stress conditions
N	number of cycles to failure
k	a constant
ϵ_p	plastic strain range

CYCLIC TEMPERATURE EFFECTS ON MATERIALS AND STRUCTURES

J.A. Dunsby*

1. INTRODUCTION

Of the many thermal problems of high-speed flight, one which appears to have received relatively little attention is that of the effect of repeated application of heat to materials and structures. In other branches of engineering the problem has long been recognized and several studies are available which are of use to the aeronautical engineer. The present survey has been prepared to outline the state of knowledge on Cyclic Temperature Effects and to suggest, where necessary, profitable avenues for future research.

The aeronautical interest in temperature cycling stems from the fact that flight missions may now subject the aircraft structure to at least one cycle of kinetic heating and cooling. The magnitude, duration and number of these cycles are, as will be seen, of the utmost importance in the choice of materials for a particular task. However, the present survey will be concerned primarily with the extent of the available data and no detailed consideration will be given to these environmental conditions.

For the purposes of discussion, it is convenient to split the cyclic temperature effects into groups. These groups are illustrated in Figure 1. As can be seen, four primary groups of effect occur, depending on the nature of the load or stress-generating mechanism. In the absence of load or external restraint, the combination of temperature and time can result in purely metallurgical changes, with accompanying changes in the mechanical properties of the material. Thermal stresses, which may result in static or fatigue-type failues, are caused by external restraint to thermal expansion, or by internal elastic restraints associated with stress gradients in a transient or non-uniform temperature field. Creep arising from repeated cycles of thermal stress may be termed cyclic temperature creep. If a steady external load is applied the material will creep until it finally fails by stress-rupture. If the external load is also cyclic in nature, failure may occur either by fatigue or by a cyclic creep process, depending on the frequency of the load. Creep under these conditions will be referred to as cyclic load creep.

In the following discussion, due to the nature of the available data, some liberties will be taken with the foregoing grouping. In particular, cyclic load creep and cyclic temperature creep will be regarded as one group.

2. EXISTING REVIEWS

The task of reviewing the literature for data on cyclic temperature effects was considerably eased by the existence of four review papers and the proceedings of two symposia[1-6]. The second part of Reference 1 surveys the state of knowledge under

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non-steady load and temperature, as does Reference 2. Reference 3 deals with the problems of failure under thermal stress and Reference 4 gives a general account of the problems of aircraft design for non-steady load and temperature. References 5 and 6, being the proceedings of symposia, provide details of some of the more important experiments which have been conducted in recent years.

3. CYCLIC TEMPERATURE AND EXTERNAL LOADS

In this Section, attention will be given to those cases in which temperature changes are sufficiently slow for there to be no significant transient thermal stresses and in which there are no external restraints. Under these conditions, any stress is due entirely to external loading.

3.1 Creep

As is well known, both creep rate and stress-rupture time are temperature-dependent quantities and data are available for a very wide range of materials at fixed temperatures and loads. A surprisingly large quantity of data is also available from tests in which cyclic variations in temperature were made, both with and without corresponding changes in load. Most of these data are reviewed in Reference 7.

Table I lists the materials for which cyclic temperature creep tests have been located. As can be seen, the majority of the materials of current interest are included.

It is reasonable to suppose that creep follows a simple cumulative process and that, when the temperature is changed, the result is merely a change in creep rate. Many tests confirm that this can be so. If, however, the temperature change is such as to induce thermal stresses or to produce metallurgical changes, the creep rate can be greatly increased.

When neither metallurgical effects occur nor thermal stresses are induced, the creep behaviour of a material under cyclic temperature conditions can be predicted reasonably accurately from isothermal creep test results. The prediction process is greatly facilitated if either a theoretical or an empirical relationship between creep rate and temperature is available.

Two such relationships have been investigated by Dorn and his co-workers. The first, which has a certain amount of theoretical background, is referred to as the θ-factor or activation energy method and makes use of the relation

$$\dot{\epsilon} = Se^{-\Delta H/RT} \phi(\sigma)$$

where
$\dot{\epsilon}$ = creep rate
S = a constant
H = activation energy
R = gas constant
T = temperature
$\phi(\sigma)$ = stress function.

The use of this method is described in References 16, 18, 19, 21 and 22. Unfortunately it is applicable only at temperatures in excess of about half the melting point of the material and then only for relatively pure materials. Figure 2(a) taken from Reference 16 shows the results of applying the θ-factor method to predict the cyclic temperature creep of 7075-T6 aluminum alloy.

While this particular example shows reasonable agreement between predicted and measured strains, this is not always the case. Reference 21, for example, presents test results which are at complete variance with the predictions of the θ-factor or any other method.

The second method, known as the K-factor method, is described in References 16, 17 and 23 and makes use of the fact that a family of creep curves at different stresses or temperatures can be reduced to a single curve if the time scales are multiplied by a constant K, this constant being a function of stress and temperature. As the method is completely empirical, a large number of experimental results are required for its application. The method has been found to be reasonably effective when applied to 0.26% carbon steel, 7075-T6 and 24S-T3 aluminum alloys, and for commercially pure titanium. The results of applying the method to cyclic temperature tests on 7075-T6 are shown in Figure 2(b). The correlation in this case is considerably better than by the use of the θ-factor method illustrated in Figure 2(a) but this should not be taken as a generalization for all materials and test conditions.

Attempts to predict the creep and stress-rupture life by means of the proportional-life concept, familiar as a fatigue cumulative damage law, have been described in several papers (see Tab.I(b)). This concept states that if a material is subjected to a stress σ and a temperature T for an interval Δt, the fraction of the life used up is $\Delta t/t_R$ where t_R is the stress-rupture time under isothermal, constant-stress conditions. Thus the condition for rupture in cyclic temperature or cyclic stress conditions is $\Sigma \Delta t/t_R = 1$.

The use of the proportional-life method has not proved to be altogether successful. The correlations obtained in References 8, 10 and 12 were very poor and in Reference 13 time errors as large as a factor of two were common. In the case of References 8 and 10, it has been suggested that the cause of the poor correlation was metallurgical effects due to the very high test temperatures.

When considering any of the methods of predicting strain rate or rupture time, the extreme sensitivity of these quantities to stress and temperature should be remembered. For example, Reference 27 indicates that, at say 1000°F, a typical sensitivity of either strain rate or rupture time to temperature is of the order 4 % per degree F. Accurate measurement of steady loads and temperatures is by no means an easy task, and when these quantities are varying the measurement becomes even more difficult. It follows that it is unreasonable to expect precise agreement between theory and experiment in tests such as those which have been described. Recognition of the experimental problems involved is made in Reference 28.

Although strictly outside the scope of the title of the present survey, the relationship between creep and fatigue is of considerable practical importance. In practice, loads are rarely steady for any significant period of time and therefore neither steady load creep tests nor tests in which loads are slowly changed represent

good approximations to practical loading. Very little work has been reported on this subject.

Reference 29 presents the results of some experiments in which a Nimonic material was tested under conditions of steady creep, cyclic temperature and load creep, and finally cyclic temperature and load creep with a fatigue loading superimposed on the steady load. In these experiments the stress-rupture life, defined as time under load, with cyclic temperature and load, was found to be some 60% less than the stress-rupture life with steady load and temperature equal to the maximum values in the cyclic tests. The addition of the fatigue loading, with the same maximum stress, was found to increase the life slightly above the value obtained in steady creep. During these tests, however, it was clear that metallurgical changes were occurring.

In Reference 30, it is reported that the addition of bending fatigue loading to a direct stress creep loading can either accelerate or decelerate creep, depending on the magnitude of the applied fatigue loading. With low fatigue loads, the creep rate was reduced, probably due to the hardening effects of such loading, while at high loads, the creep rate was accelerated. References 31 and 32 describe some most interesting experiments which indicate that a minor fatigue loading can have significant effects on relaxation following a creep loading and on the creep rate itself.

3.2 Fatigue

Mechanical fatigue is also a temperature-dependent phenomenon and a substantial body of data exists for isothermal fatigue tests at elevated temperatures. However, the author has been unable to trace any test results in which the temperature was cycled or even varied independently of the load apart from those of Reference 29 described earlier. This absence of data is somewhat surprising as it is clear that a supersonic vehicle will accumulate fatigue damage due, for example, to gust loading, under both subsonic low-temperature and supersonic high-temperature conditions. Some knowledge of the cumulative damage laws under these conditions is obviously essential. Reference 33 also draws attention to this lack of data.

It should be noted that although, as has previously been stated, there exists a substantial body of data on isothermal elevated-temperature fatigue, there remain many gaps to be filled. In particular reliable, statistically significant tests under practical structural loading conditions, i.e. in direct stress, are available for very few materials. Elevated-temperature tests on specimens containing stress raisers are particularly sparse. Effects such as those of overaging on fatigue strength have received very little attention.

3.3 Static Strength and Metallurgical Effects

The temperature dependence of static strength is too well known to require discussion. Attention should, however, be drawn to the influence of time at temperature on the static strength of a material. When a material is held at an elevated temperature for any significant time, aging and overaging may occur, and this generally results in a loss in static strength. Such effects are well known and are concisely described in, for example, Reference 34. In most investigations on the effect of time at temperature on static properties, attention is confined to a single temperature exposure. Two series of experiments, listed in Table II, have been traced, however, in which the

temperature exposures were made sequentially. These both showed, for aluminum alloys, that the effect of sequential exposures was virtually identical to that of a single exposure for the same total period.

A metallurgical effect, unlikely to be of importance for materials used in airframes, which also occurs with temperature cycling is the formation of scale and its subsequent loss due to repeated differential expansion and contraction. Tests to determine the scaling resistance of the Iron-Chromium-Nickel alloys are reported in Reference 37.

One further phenomenon which occurs when the temperature of non-cubic metals is cycled is that of an anisotropic growth. This subject has received much attention in the case of Uranium[38] and a lesser attention for Cadmium, Zinc and Tin, but it is reported that such growth does not occur with any other commonly used metals or alloys. In particular, the growth is restricted to non-cubic metals.

4. THERMAL STRESS EFFECTS

4.1 Stresses due to External Restraints

Many examples can be found in practice of a structural element whose thermal expansion is wholly or partially restrained by another member. Such conditions may be encountered in a structure at a uniform temperature if materials having differing temperature coefficients of expansion are used, or alternatively, may occur at the junction of hot and cold members.

Under such conditions, a single application of temperature may suffice to generate stresses of sufficient magnitude to fail the structure. Design to avoid this is relatively simple in most cases since the only information required is the static strength or buckling strength of the member at elevated temperature together with the temperature coefficients of expansion.

If the single application of temperature is insufficient to cause failure, repeated applications may result in the accumulation of fatigue damage with an eventual failure from this cause. Such a failure cannot at present be predicted from isothermal fatigue test results as the damage is accrued under a range of temperature.

Table III lists the experiments which have been reported on the temperature cycling of externally restrained materials. The data are not extensive but are sufficient to provide a broad outline of the failure process. In each case it was found that failure occurred after the specimen had been subjected to a substantially smaller number of cycles than if it had received the same stress or strain range mechanically at the same mean temperature. Typical results of experiments at constant mean temperature are illustrated by Figure 3 taken from Reference 43, while Figure 4, taken from Reference 6, illustrates the effect of mean temperature.

In many of the tests reported, the conditions were such that the elastic limit was exceeded during the cycle and plastic straining occurred. Under these conditions, if the specimen is clamped either hot or cold, it eventually shakes down until the ranges of positive and negative stress or strain are virtually the same. It has been shown by Coffin that the data from these tests can be correlated by the method proposed by

Manson[44] and, for a given mean temperature, obey a law of the form $N^k \epsilon_p = \text{const}$, where N = number of cycles to failure, k = a constant, ϵ_p = plastic strain range. The constant k has been found generally to take a numerical value very close to 1/2 and Coffin has suggested that it should always have precisely this value, changes being due to time-dependent phenomena such as creep and other diffusional processes which may be allowed for separately.

In the case of the tests on low ductility nickel-base alloys reported in Reference 45, the plastic strains were too small to be measured with any accuracy and correlation on a plastic strain basis was found to be impracticable. A noteworthy inclusion in Reference 45 is reference to the little known fact that the coefficient of thermal expansion of a material is itself stress-dependent, as was demonstrated in Reference 46.

Most of the data on restrained thermal cycling are restricted to tests with relatively small numbers of cycles by the standards of conventional fatigue tests. These numbers are, however, adequate when considered as numbers of missions of a supersonic aircraft; this point will be discussed at further length in Section 5.

The range of materials covered by the existing test results is not extensive and it is considered that tests on other materials are highly desirable. Also, in only one group of tests[40] have experiments been made under conditions other than those of full constraint. With further experiments should come attempts at analysis with the particular objective of predicting the thermal fatigue life from isothermal fatigue data.

4.2 Stresses due to Internal Restraints

Thermal stresses may be generated by a temperature gradient through a material, in which case the restraint inducing the stress is internal. Such temperature gradients may be transient in nature, as when the material is being heated or cooled rapidly to a uniform temperature or may be steady due to the fact that the material is steadily conducting heat from one part of the structure to another. In both cases the thermodynamic properties of the material, e.g. conductivity and specific heat, play an important part in determining the magnitudes of the thermal stresses.

Transient thermal stress effects have received a fair amount of attention in tests usually referred to as thermal shock and repeated thermal shock. In such tests, the specimen is heated as rapidly as possible by high-frequency induction, electrical conduction, or other means, and rapidly cooled by an air blast or by immersion in water. Under these conditions it is found that beyond a certain temperature range brittle materials will frequently fail statically in a single cycle while ductile materials will withstand a number of cycles and fail by a fatigue process. Typical results are illustrated in Figure 5.

Unfortunately, thermal shock tests are very difficult to perform since, for them to be of value, the transient rates of heat transfer must be both controlled and measured. In none of the reported tests, with the exception of the limited tests of Reference 48, have any serious attempts been made to measure the heat transfer rates. It therefore follows that although Table IV lists a large number of materials which have received thermal shock tests, there is not likely to be any simple correlation between tests made with the different types of apparatus.

The problem of a single thermal shock has been treated theoretically by several authors (see, e.g., Refs.44 and 46). In the case of repeated thermal shock, when once more fatigue damage is accrued over a range of temperature, it would not seem possible with the present state of knowledge to attempt any theoretical or empirical solution.

The problem of repeated thermal shock is obviously simply related to that of temperature cycling of a restrained member and as the latter presents a much simpler experimental problem it is possible that it is from this direction that a solution to the problem of repeated thermal shock may come.

5. CYCLIC HEATING EFFECTS IN RELATION TO COMPLETE STRUCTURES

The preceding sections have outlined the data which are available for materials subjected to thermal cycling. The published data on cyclic temperature effects in structural components or in complete structures are sparse, References 4, 53, 54 and 20 being the only papers which have been located. Of these four references, the first three can only be described as being speculative, containing calculations on the effects which might be expected, but no supporting experimental data.

Reference 20 describes extensive cyclic load and temperature creep tests on riveted joints of 2024-T3 clad aluminum alloy and riveted and spot-welded joints of 17-7PH(TH 1050) stainless steel. The results of these tests showed a wide variance but it was found that the times for stress rupture or for a specified elongation could be predicted from material data under corresponding conditions to within a factor of 2; this would correspond to a discrepancy in stress of less than 10%.

Apart from the more obvious gaps in knowledge of the behaviour of specific materials and in phenomena such as the cumulative fatigue damage laws under variable-temperature conditions, very little information is available on such subjects as stress raisers and cyclic temperature buckling, References 4, 39 and 20 containing the only data which have been located. No published experimental results at all have been located in which complete structures have been subjected to cyclic thermal effects although it is clear from numerous published references to experimental equipment, e.g. Reference 55, that such experiments are contemplated or have been conducted.

A most important factor in the planning or analysis of cyclic temperature tests is the nature of the load and temperature spectra. These will, of course, depend on the nature of the mission for which a particular vehicle is intended. Some studies on the load spectra are described in Reference 4 and it is concluded that a suitable load-time distribution can be derived from existing records for subsonic aircraft in most instances. The temperature-time distributions on the other hand present some difficulties. For the purposes of the structural studies given in Reference 4, it is assumed that for both fighters and bombers half an hour is accumulated at elevated temperature on each of 1000 supersonic missions. This number of missions might be considered uneconomically small for many purposes and it is suggested that for the purposes of basic research, 10,000 cycles is a more practical number. The highest rate of kinetic heating or cooling to which an airframe could be subjected is that due to an instantaneous change in speed and thus presents little difficulty in estimation.

6. DISCUSSION

The purpose of this survey is to determine the areas in which further research is most needed. It is convenient therefore to summarize the state of knowledge in each of the areas previously described, and to examine the gaps in the available data.

(i) Cyclic temperature creep is partially understood and methods exist which, within certain limitations, have been demonstrated to be able to predict cyclic temperature creep from isothermal creep data. Outside these limitations, there is an abundance of experimental data from which estimates of creep can be made on a wholly empirical basis and with little understanding of the fundamental mechanism involved.

(ii) Almost no results have been located on cyclic temperature fatigue although this appears to be a subject of considerable future importance. Possibly even more important is the fact that reliable isothermal fatigue data under representative loading conditions are relatively scarce and even simple effects such as those of overaging have received little attention.

(iii) From two isolated series of tests on aluminum alloys it appears that any metallurgical effects induced by pure temperature cycling follow a simple cumulative process and can be determined from data obtained from tests using a single temperature exposure of corresponding duration.

(iv) Data from tests in which the temperature of an externally restrained specimen is cycled are restricted to five high-temperature alloys and two commercially pure metals. Furthermore, in only one of these tests was the specimen subjected to conditions other than full restraint. No methods are available to enable prediction of material life to be made under these conditions.

(v) Many test results are available for materials subjected to repeated thermal shock but in few instances have transient heat transfer rates been accurately controlled or measured. The results of these tests can, therefore, only be regarded as being comparative.

(vi) No experiments on complete structures subjected to thermal cycling have been reported nor are results available on cyclic temperature buckling under these conditions. Data on stress raisers are also severely limited.

7. CONCLUSION

It is apparent that there are at present no means whereby the extensive results of many years of isothermal fatigue testing can be used to provide solutions to similar problems when the effects of variable temperature and the time-dependent phenomena of creep and stress relaxation are added to any significant extent.

Undoubtedly it will be many years before the fundamental metal physics phenomena are clearly understood either for creep in the absence of fatigue or for fatigue in the absence of creep. It is therefore apparent that engineering design needs have leaped far ahead of scientific understanding and that criteria of design for concurrent thermal cycling and cyclic loading can expect little from fundamental research and not much more from the empiricism of the past few decades.

To resolve this impasse, there are only two alternatives; either to intensify the effort in fundamental work or to create and employ a yet more complex systematization of empirical findings for purely engineering design purposes.

Since it would appear to be impossible to bring any useful pressure to bear on the solution of fundamental problems beyond that currently existing, the conclusion must be that the second of these alternatives is both justified and imperative.

To assist in the selection of suitable experiments to support such systematization, there are contained in the Appendix a number of suggestions for further study.

8. ACKNOWLEDGMENTS

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TABLE I

Cyclic Temperature Creep

(a) *Experimental Results*

Material		Reference
Type 321	Stainless steel	7
N-155	Heat-resisting austenitic alloy	
Inconel 'X'	Nickel alloy	
RC-130A	Titanium alloy	
FS-IH	Magnesium alloy	
24S-T3	Aluminum alloy	
Inconel	Nickel alloy	8
25-20	Stainless steel	9
18-8	Stainless steel	
18 Cr, 8 Ni (0.03C)	Stainless steel	10
18 Cr, 1/2 Mo.	Stainless steel	
18 Cr, 8 Ni (Ti)	Stainless steel	
4130	Low-alloy steel	11
RC 70	Titanium	
Type 347	Stainless steel	12
S-816	Cobalt-base alloy	13
M-252	Nickel-base alloy	
16-25-6	Heat-resisting austenitic alloy	
A-286	Heat-resisting steel	
24S-T3	Aluminum alloy	11, 14
75S-T6	Aluminum alloy	
7075-T6	Aluminum alloy	15, 16, 17
	Pure aluminum	18
	Pure nickel	19
	Five nickel-base alloys	20
	Tantalum	21

(b) *Analytical Methods*

Method	*Reference*
θ-factor	16, 18, 19, 21, 22
K-factor	16, 17, 23
Proportional life	10, 12, 24, 25, 26

TABLE II

Effect of Temperature Cycling on Static Strength

Material		Reference
2024-T3	Aluminum alloy	35
7075-T3	Aluminum alloy	
AZ 8 GU	Aluminum alloy	36

TABLE III

Thermal Cycling of Externally Restrained Specimens

Material		Reference
Type 347	Stainless steel	39, 40
S-816	Heat resisting cobalt alloy	41, 42
Inconel 550	Heat resisting nickel alloy	
Ti-75A	99.7% titanium	43
Type A Nickel	(99.58%)	

TABLE IV

Repeated Thermal Shock

Material		*Reference*
Type 304	Stainless steel	47
Type 310	Stainless steel	
N-155	Heat-resisting austenitic alloy	
Waspalloy	Heat-resisting nickel alloy	
Hastelloy	Heat-resisting nickel alloy	
Inconel	Heat-resisting nickel alloy	
Nimonic 80A	Heat-resisting nickel alloy	
M-252	Heat-resisting nickel alloy	
HS-21	Heat-resisting cobalt alloy	
S-816 (cast)	Heat-resisting cobalt alloy	
S-816 (wrought)	Heat-resisting cobalt alloy	
S-816 (cast)	Heat-resisting cobalt alloy	49
S-590	Heat-resisting austenitic alloy	
Vitallium	Heat-resisting cobalt alloy	
422-19	Heat-resisting cobalt alloy	
X-40	Heat-resisting cobalt alloy	
Stellite 6	Heat-resisting cobalt alloy	
En 25	2 1/2% Ni-Cr-Mo steel	50
	Si-Cr valve steel	
Nimonic 90	Heat-resisting nickel alloy	48
Nimonic 75	Heat-resisting nickel alloy	51
Nimonic 80A	Heat-resisting nickel alloy	
Nimonic 90	Heat-resisting nickel alloy	
Inconel	Heat-resisting nickel alloy	

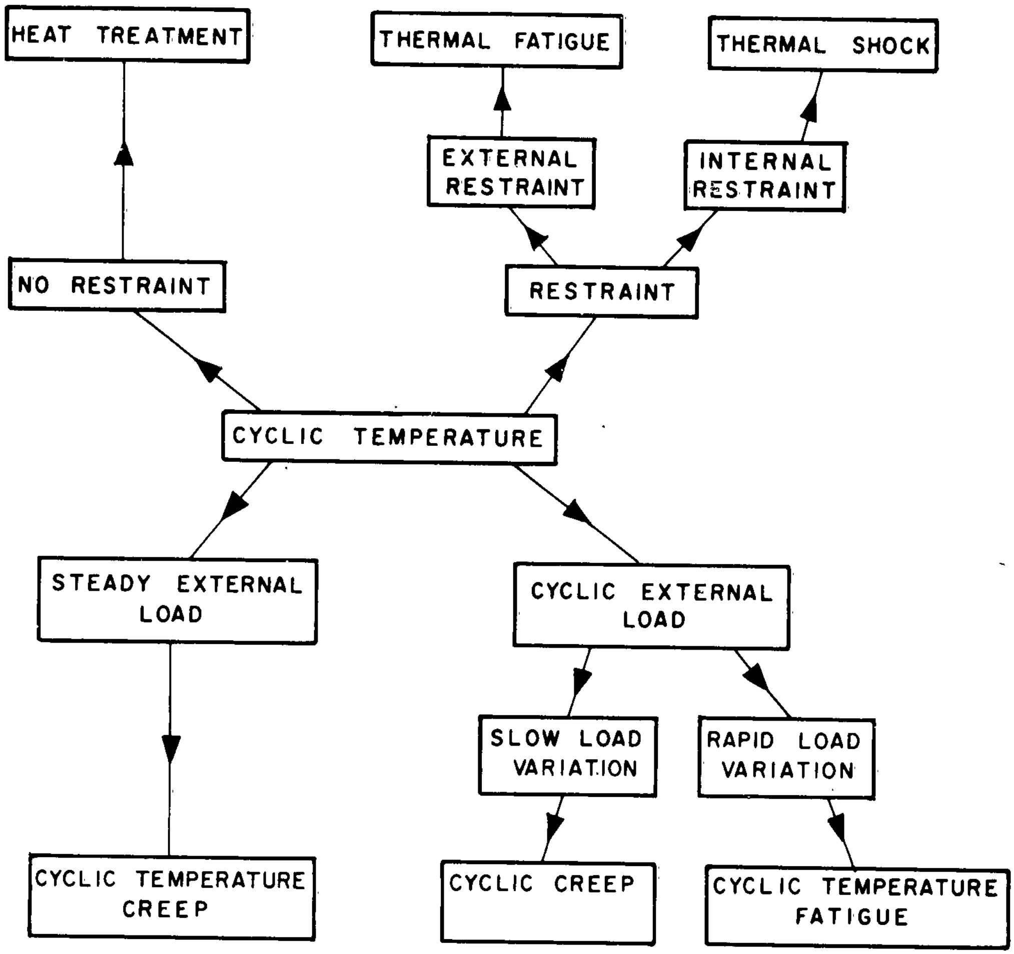
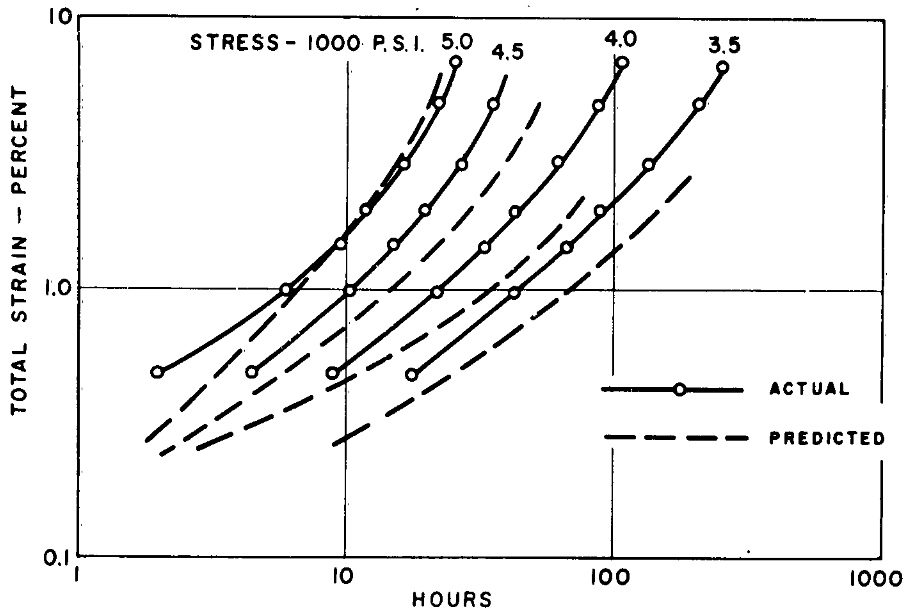


Fig.1 Cyclic temperature effects

(a) θ-factor



(b) K-factor

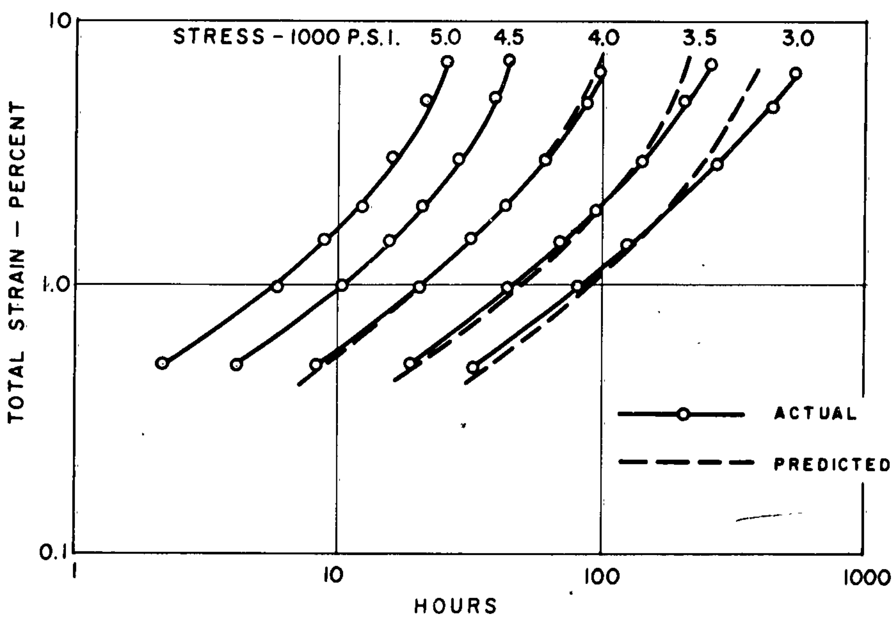


Fig.2 Method of estimating cyclic temperature creep (Data from Ref.16. 7075-T6 cycled from 550°F to 600°F)

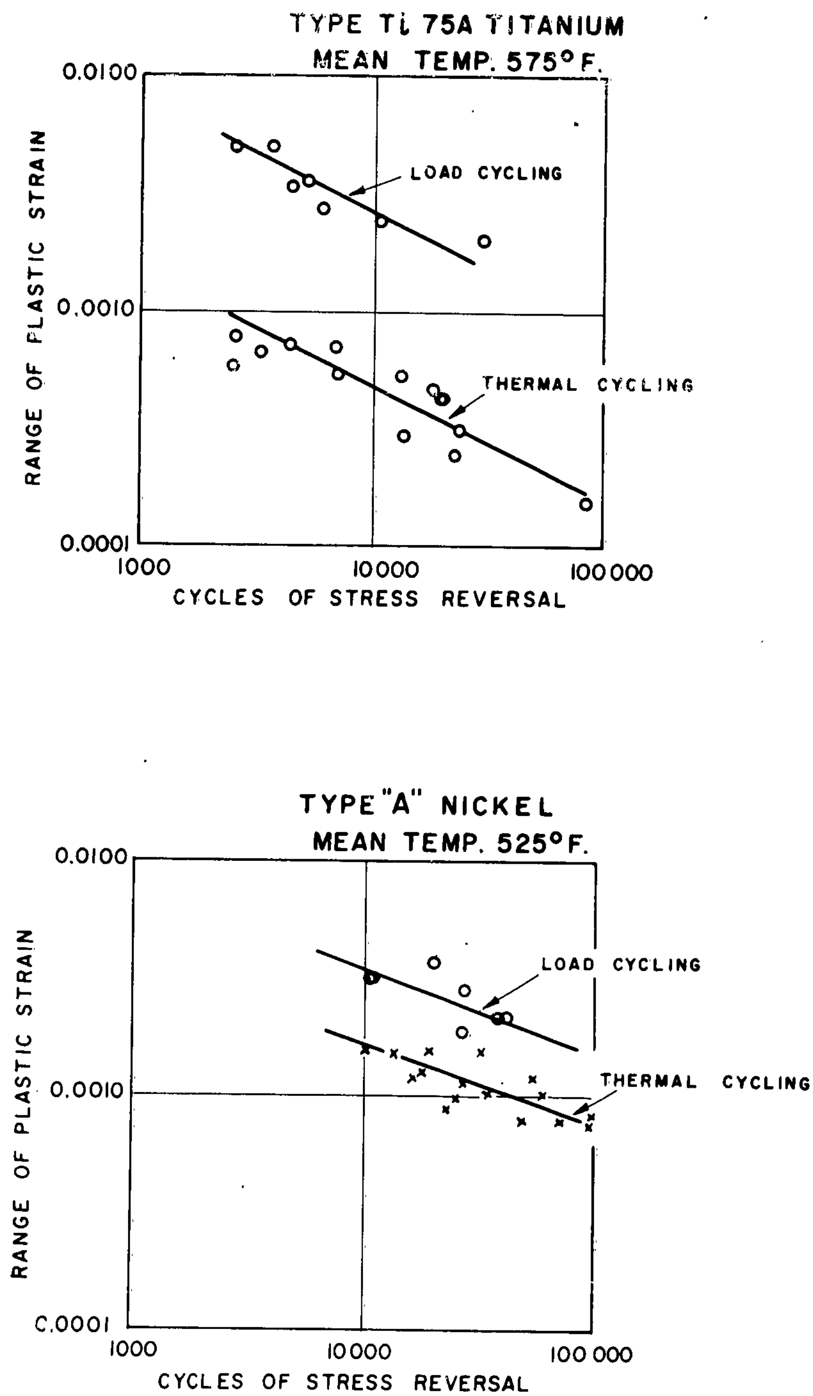


Fig. 3 Comparison of restrained thermal cycling with load cycling (From Ref. 39)

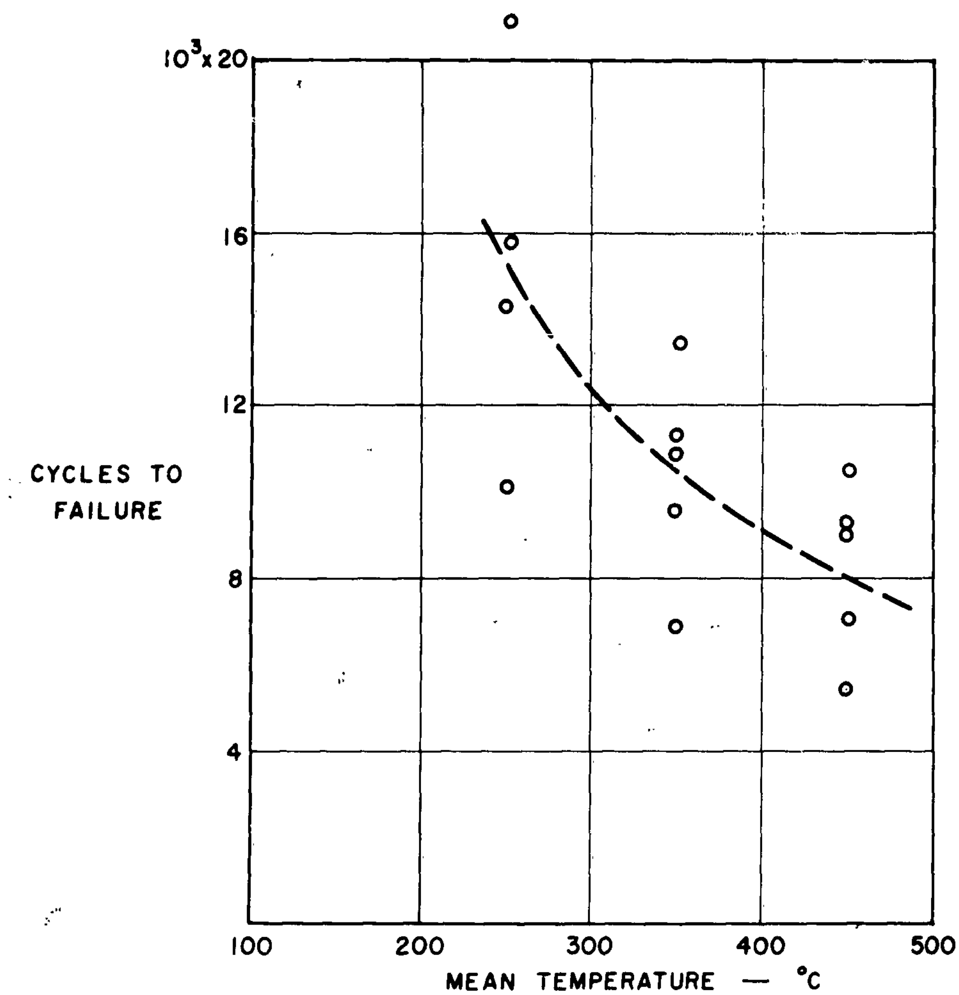


Fig. 4 Effect of mean temperature on cycles to failure for type 347 stainless steel subjected to restrained thermal cycling over a range of 300°C (from Ref. 6)

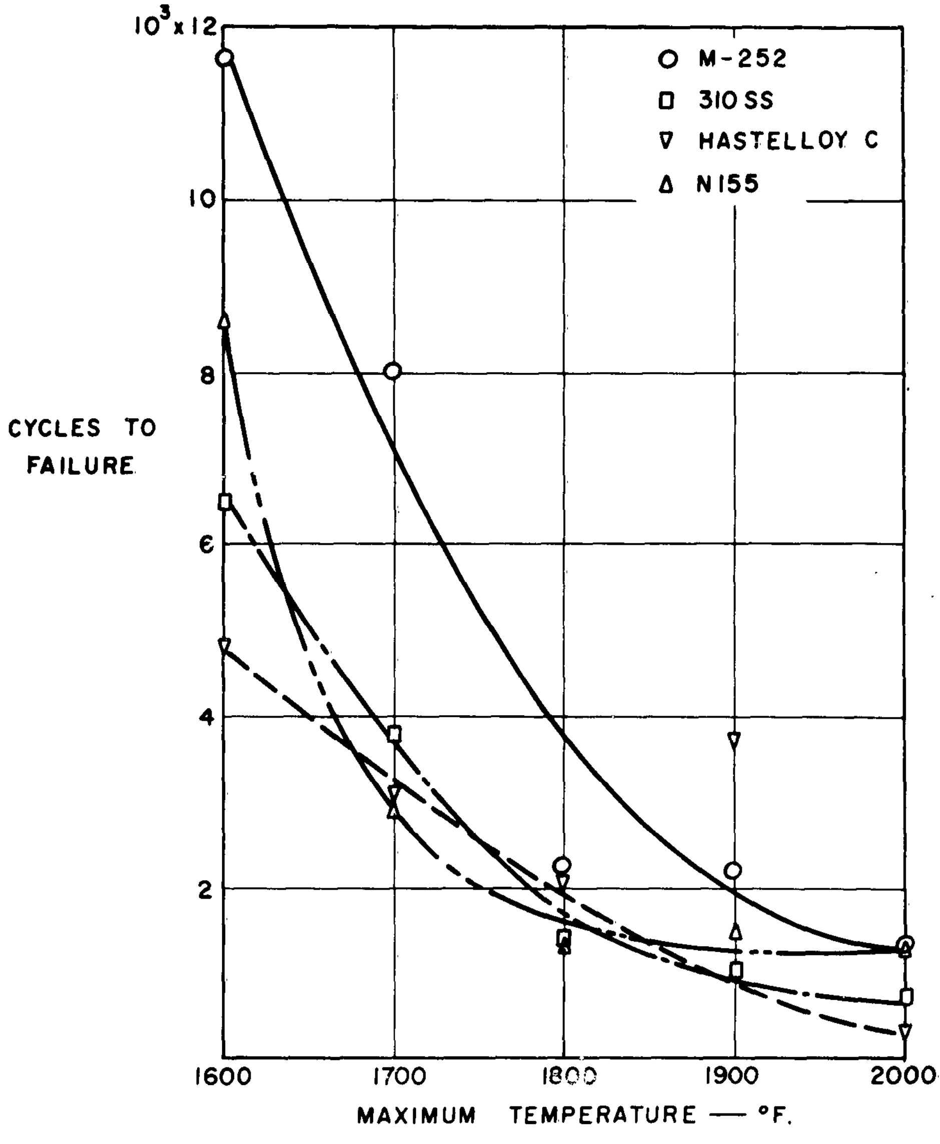


Fig.5 Effect of maximum temperature on resistance to repeated thermal shock (from Ref. 45)

APPENDIX

Suggestions for Further Research

1. SIMPLE FATIGUE

(a) Constant elevated temperature fatigue tests under direct stress, (i.e. tension-tension and tension-compression) of the more common aeronautical materials both with and without stress raisers. The test programme should be sufficiently extensive to establish the fatigue characteristics on a statistical basis.

(b) Constant temperature fatigue tests to determine the effects of time at temperature on fatigue strength at both room and elevated temperature.

(c) Tests to determine the effect of rest periods on fatigue strength at elevated temperature. In an elevated temperature fatigue test of most heat-treatable materials, fatigue damage and metallurgical changes will occur concurrently. It is therefore to be anticipated that the measured fatigue strength will depend on the duration of the test, i.e. there will be a frequency effect over and above that normally encountered at room temperature. Relatively few fatigue machines can be operated over a sufficiently wide frequency range to investigate this phenomenon but a reasonable alternative to obtain data of engineering value is to apply the fatigue loading intermittently. By this means the average frequency can be reduced. Expressed in another way, this amounts to having rest periods at elevated temperature.

2. CYCLIC TEMPERATURE FATIGUE

(a) In order to obtain an understanding of the more general problem of fatigue with cyclic temperature variation, it would be useful to conduct experiments in which there is a single step change in temperature during the fatigue loading. For such experiments it would be permissible to remove the load during the temperature change, thus the specimen might respond as though a step change in temperature had occurred. This condition is probably more susceptible to analysis than a progressively increasing or decreasing temperature.

(b) The general problem of determining cumulative damage rules for fatigue under varying load and temperature ranges probably involves too many parameters for the efforts of a single laboratory to be of much significance. Co-operative research in this area is therefore to be encouraged. Initially the obvious problem to study is that of the cumulative effects of temperature change when the load range is held constant. Data obtained from the experiments suggested in Item 2(a) will provide useful guidance on this problem and a logical, but more difficult, extension of the experiments would be to study the effects of repeated cycles of temperature.

3. THERMAL FATIGUE

While there are already useful data available on the endurance of a restrained specimen upon which a cyclic temperature is imposed, further work is required in order to provide data from which the relationship between the endurance under this type of loading and that in isothermal fatigue may be obtained.

4. THERMAL SHOCK

Experiments on thermal shock and on repeated thermal shock in which heat transfer rates or temperature gradients are both controlled and measured are obviously necessary before any hypothesis to predict endurance under these conditions can be propounded. For the experiments to be of real value, measurements must also be made of the physical properties of the test materials which are known to influence the endurance, i.e. coefficient of expansion, conductivity, modulus of elasticity and static creep and fatigue strengths over the range of temperatures involved.

5. CREEP AND FATIGUE INTERACTIONS

5.1 Concurrent Creep and Fatigue

In the existing data on cyclic load creep, the numbers of cycles of load applied have, in general, been so small that the failure process is essentially that of creep. Conversely, in elevated-temperature fatigue tests frequencies and loads have been such that the failure process is essentially fatigue. It is evident that at some intermediate frequency, dependent on stress level and temperature, failures which are a combination of the two processes will occur. Experiments using appropriate loading frequencies to determine the results of the interaction of concurrent fatigue and creep would be of obvious practical interest.

5.2 Serial Creep and Fatigue

In addition to the relatively simple problem of the interactions of concurrent creep and fatigue, situations are likely to arise in practice in which creep and fatigue occur sequentially and not necessarily at the same temperature. Experiments aimed at obtaining data from which the cumulative damage laws under these loading conditions can be formulated are required. Initially such experiments might be restricted simply to cover fatigue to various proportions of life followed by creep rate and rupture time measurements and vice versa. These experiments can readily be performed with conventional creep and fatigue testing machines. Subsequently it will be necessary to conduct more complex tests in which the creep-fatigue sequence is applied in a number of cycles. For this latter, the development of suitable testing equipment will pose several problems (see Ref.28).

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